A STUDY ON THE PERFORMANCE OF LIMESTONE ROUGHING FILTER FOR THE REMOVAL OF TURBIDITY, SUSPENDED SOLIDS, BIOCHEMICAL OXYGEN DEMAND AND COLIFORM ORGANISMS USING WASTEWATER FROM THE INLET OF DOMESTIC WASTEWATER OXIDATION POND

by

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Thesis submitted in fulfillment of the requirements for the degree of Master of Science

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DEDICATION

To my supervisor Associate Professor Dr Ir. Hj. Mohd Nordin Adlan and Co Supervisor Associate Professor Dr Hamidi Abdul Aziz, without their helpful guidance, efforts and wise suggestions, my pursuit of higher education would not been possible and I would not have had the chance to work for a master degree.

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LIST OF SYMBOLS AND ABBREVIATIONS

The following tabulation lists the symbols used in this thesis. Because the alphabet is limited, it is impossible to avoid using the same letter to represent more than one concept. Since each symbol is defined when it is first used, no confusion should result.

Symbol	**Descriptions**
APHA	American Public Health Association
mm	milimeter
NTU	Nephelometric Turbidity Unit
TSS	Total suspended solids
BOD	Biochemical oxygen demand
MPN	Most probable number
DO	Dissolved oxygen
ha	hectare
mg	miligram
s	second
ppm	Part per million
Q	Volumetric flow rate
lps	Liter per second
HRF	Horizontal flow roughing filter
DRF	Down flow roughing filter
URF	Up flow roughing filter
m	meter
SSF	Slow sand filter

ml	mililiter
h	Headloss
C_D	Drag coefficient (dimensionless)
R_e	Reynolds number (dimensionless)
L	Length (m)
v	Kinematic viscosity of fluid (m^2/s)
d	Particle diameter (μm)
ψ	Shape or sphericity factor (<1)
V	Flow rate ($m^3/m^2/h$)
f	prosity
d_g	Gravel size (mm)
d_o	Pore size (mm)
d_p	Particle size (μm)
d_s	Settling distsance (cm)
v	settling velocity in (cm/s)
g	acceleration due to gravity in (cm/s^2)
d	diameter of particle in (cm)
ρ_p	particle density in (gm/cm^3)
ρ_w	fluid density in (gm/cm^3)
μ	fluid viscosity in (gm/cm/s)
pH	Potent hydrogen
° C	Degree celsius
E. coli	*Escherichia coli*
TC	Total coliform
FC	Fecal coliform

mV	milivolt
SSA	Specific surface area
C	Solid concentration
z	Filter depth (m)
λ	Filter coefficient
E	Filter efficiency
V_f	Flow rate (m/h)
μ	Population mean
$\bar{x}$	Sample mean
s^2	Sample variance
σ	Population standard deviation
s	Sample standard deviation
IQR	Interquartile range
ANOVA	Analysis of variance
df	Degree of freedom
hr	hour

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KAJIAN PRESTASI PENAPIS KASAR BATU KAPOR UNTUK PENYINGKIRAN KEKERUHAN, PEPEJAL TERAMPAI, KEPERLUAN OKSIGEN BIOKIMIA DAN ORGANISMA KOLIFOM DARIPADA TAKAT MASUK AIR SISA DOMESTIK KOLAM PENGOKSIDAAN

ABSTRAK

Penurasan kasar pada hakikatnya adalah bertujuan untuk melindungi penapis pasir perlahan dengan cara mengurangkan kekeruhan influen dan pepejal terampai pada tahap yang mana ianya boleh beroperasi dengan berkesan. Penurasan kasar menyediakan suatu kaedah yang bertujuan untuk memperbaiki kualiti air kumbahan tanpa menggunakan sebarang jenis bahan kimia. Selain daripada melindungi penapis pasir perlahan, kaedah ini juga boleh memastikan olahan air kumbahan sebelum ianya dibuang sebagai air luahan dan dapat diguna semula.

Kajian ini bertujuan untuk mengkaji kebolehan penuras kasar batu kapur (limestone) untuk mengurangkan tahap kekeruhan, pepejal terampai, keperluan oksigen biologi (BOD) dan organisma “coliform” (bakteria) yang terkandung dalam air sisa atau air kumbahan. Kajian ini melibatkan empat peringkat. Setiap peringkat melibatkan medium penuras batu kapur (limestone) yang berlainan saiz iaitu, media penuras bersaiz kecil (1.91 mm), bersaiz sederhana (4.9 mm), bersaiz besar (16.28 mm), dan gabungan daripada kesemua saiz tersebut. Air kumbahan daripada loji olahan kumbahan telah digunakan sebagai sampel air tercemar yang mana ianya telah dikaji melalui media penuras kasar dengan enam jenis kadaralir yang berbeza. Kesemua sampel telah diuji di Makmal Persekitaran Universiti Sains Malaysia.

Keputusan daripada eksperimen tersebut, didapati bahawa penuras kasar batu kapur yang telah digunakan berupaya mengurangkan tahap kekeruhan antara 74.63% hingga 92.07%, pepejal terampai dikurangkan antara 79.25% hingga 88.2%, organisma kolifom dikurangkan sebanyak 67.44% hingga 96.09%, manakala BOD berkurangan antara 51.28% hingga 67.19%.

Kecekapan penuras kasar batu kapur bergantung kepada saiz medium dan kadar alir yang digunakan. Saiz medium yang lebih besar menghasilkan kecekapan penurasan yang kecil dan sebaliknya, manakala kadar alir yang lebih perlahan akan menghasilkan kecekapan penurasan yang tinggi dan sebaliknya. Kecekapan penurasan juga dapat ditingkatkan dengan menambah lapisan kotor yang menutupi medium penuras seperti “biofilm”.

Secara amnya, penuras kasar adalah suatu kaedah teknologi olahan yang murah dan mampu menghasilkan air yang selamat untuk bekalan air yang mana ianya dapat mengurangkan tahap kekeruhan dan pepejal terampai daripada air sisa atau kumbahan dari suatu kawasan tertentu. Selain daripada itu, penuras kasar juga adalah suatu kaedah yang sesuai untuk olahan air sisa kerana ianya mampu mengurangkan organisma kolifom dan pepejal organik sebelum diguna semula.

A STUDY ON THE PERFORMANCE OF LIMESTONE ROUGHING FILTER FOR THE REMOVAL OF TURBIDITY, SUSPENDED SOLIDS, BIOCHEMICAL OXYGEN DEMAND AND COLIFORM ORGANISMS USING WASTEWATER FROM THE INLET OF DOMESTIC WASTEWATER OXIDATION POND

ABSTRACT

The original purpose of roughing filtration is to protect slow sand filters by reducing influent turbidity and suspended solids to a level that is effective for operation. Roughing filtration presents a promising method for improving raw water quality without using any chemicals. Roughing filter is not only used to protect slow sand filters but also for the treatment of wastewater before it is discharged to the environment or reused.

The aim of this research is to study the capabilities of limestone roughing filter for the removal of turbidity, suspended solids, biochemical oxygen demand and coliform organisms. This study involved four different batches of experiments. Each experiment used different sizes of limestone filter media, such as small size (1.91 mm), medium size (4.9 mm), large size (16.28 mm) and a combination of those filter media respectively. Wastewater from the influent of oxidation pond was used as water samples in this experiment and it was passed through the roughing filter at six different flow rates. Both unfiltered and filtered water samples were collected and tested at the Environmental Engineering Laboratory of Universiti Sains Malaysia.

The experimental results indicate that roughing filter has an average turbidity removal of 74.6% to 92.1%, suspended solids removal of 79.3% to 88.2%, coliform organisms removal of 67.4% to 96.1% and BOD removal of 51.3% to 67.2%.

The removal efficiency of limestone roughing filter depends on the size of filter media and applied filtration rates. The bigger size filter media gave the lower removal

efficiency than smaller filter media. At lower flow rate, the removal efficiency was higher than at higher flow rate. Removal efficiency increased when the filter media was covered with dirty layer called biofilm.

Overall, roughing filtration is an appropriate technology for the treatment of wastewater because it could reduce coliform organisms and organic solids from wastewater, before it is reused or discharged.

CHAPTER 1
INTRODUCTION

1.0 The Need for Treating Water and Wastewater

Through out history, water has played an important role because of its use for drinking, bathing, washing dishes, laundry, cooking, watering the plants and so on. Therefore, water supply has become essential for the development of human civilization. Generally, water supply systems can be divided into two categories depending on the sources, namely surface and ground water supplies. The majority of sources for water supply are surface water. For example in Malaysia, rivers, streams and lakes provide more than 90% of the current Malaysian water needs (Sastry *et al*., 1996). Wherever possible, a water source that provide good quality water should be one which does not require treatment. However, surface water and ground water are subjected to contamination from many sources, which could cause risk to human health. Therefore, treatment of water is required to remove those contaminants.

As rainfall runs over the surface of structures and grounds, it may pick up various contaminants including soil particles, organic compounds and animal wastes and so on. Sometimes, it is required to receive some level of treatment before being discharged to the environment. Especially household wastewater or sewage includes disease-causing bacteria, infectious viruses, and household chemicals. If too much untreated sewage is released to the environment, dissolved oxygen level may drop and some species of fishes and other aquatic life may die. Therefore, wastewater also needs to be treated before it is discharged to the environment (Barnes *et al*., 1986).

1.1 Roughing Filtration

Filtration is one of the oldest and simplest methods of removing those contaminants. Generally, filtration methods include slow sand and rapid sand filtration.

The slow sand filters constructed in rural communities show that many of these filters have short filter run and produce turbidity in the excess of the WHO guideline values for drinking water (Ali, 1998). Reliable operation for sand filtration is possible when the raw water has low turbidity and low suspended solids (Graham, 1988). For this reason, when surface waters are highly turbid, ordinary sand filters could not be used effectively. Therefore, the roughing filters are used as pretreatment systems prior to sand filtration (Jayalath and Padmasiri, 1996). Furthermore, roughing filters could reduce organic matters from wastewater. Therefore, roughing filters can be used to polish wastewater before it is discharged to the environment.

Although roughing filtration technology is used as pretreatment to remove turbidity and followed by slow sand filtration, it may be used without slow sand filtration if raw water originates from well protected catchment and if it is free from bacteriological contamination (Wegelin, 1996). Roughing filters make natural purification processes and no chemicals are necessary. Besides these filters could be built from local materials and manpower. These filters will work a long time without maintenance (Wegelin, 1986). Therefore, roughing filters are appropriate and economical for rural water supply schemes.

1.2 Research Objectives

The main objective of this research is to study and evaluate the removal of turbidity, suspended solids, biochemical oxygen demand and coliform organisms from wastewater using limestone roughing filter. This study also tried to relate between flow rate and removal efficiencies. Furthermore, this research also studies on the improvement ability of the filter due to ripening.

1.3 Thesis Summary

The thesis is organized as follows:

a) Chapter 1 provides an introduction of the thesis

b) Chapter 2 presents the literature review consisting of removal capabilities of roughing filter, roughing filter theory and characteristics of water parameters.

c) Chapter 3 presents the procedures and methods of the research.

d) Chapter 4 describes the results and discussion of the experiments.

e) Chapter 5 is the conclusions and recommendations of the research.

f) The list of references is given at the end of this research and

g) Appendices.

CHAPTER 2
LITERATURE REVIEW

2.0 Importance of Water Treatment

Water is never found pure in nature. Even rain water which is the nearest form of pure water may contain small amount of dusts and dissolved gases, such as oxygen and carbon dioxide taken from the air. Therefore, whatever may be the source water will have impurities. Thus, water needs to be treated. Water with standard quality is used for drinking, washing, industrial and agricultural activities and others. Water quality varies from source to source and quality requirement varies according to its usage (Sastry *et al*., 1996). In earlier times, man used water from natural sources. In order to get more or better quality of water, man moved to other sources. Man's earliest standards on water quality were such as free from mud, bad taste and odor. However, an increase in man-made water pollution, the development of technical and public health science, as well as the consumers' greater need for clean water contributed to the development of the water purification technology (Wegelin, 1996).

Since 1990, the number of people without access to safe water source has remained constant at approximately 1.1 billion of whom approximately 2.2 million die due to water borne diseases each year. In developing countries, providing safe water for all is necessary (Mintz *et al*., 2001). The techniques, the quality of purified water and the composition and design of treatment works depend in each particular case on the quality of raw water and the desired standards of treated or product water. When several methods of water treatment are available, the best method or sequence of methods is chosen based on technical as well as economical analyses. Cost and local factors such as availability of construction materials also have influence on the selection and design of treatment units (Sastry *et al*., 1996).

2.1 Brief History of Water Treatment

The old Hebrew, Sanskrit, and Greek writings revealed that impure water should be treated by boiling or by filtering through crude sand or charcoal. By 2000 B.C., people in India have been known to have filtered water through charcoal and stored it in copper pots for later use. Figure 2.1 is the picture of earliest known clarifying apparatus, excavated from the walls of Egyptian tombs of 15^{th} and 13^{th} century. The Egyptian operators allowed impurities to settle out of the liquid, siphoned off the clarified fluid using wick siphons and, finally, stored it in pots for later use (Jesperson, 2005).

Figure 2.1: Ancient Egyptian Clarifying Device (Source: Jesperson, 2005)

Filtration is one of the methods for the treatment of water and it is one of the oldest, simplest and widely used methods. Simplicity of filtration makes the process attractive for use in small communities and developing nations. It is the process of removing suspended solids from raw water by passing the water through a permeable fabric or porous bed materials. For large quantity of water, sand is generally used as the filter medium, because it is inexpensive and effective (Weber-Shirk and Dick, 1994; Sastry *et al*., 1996).

Water treatment plants have successfully used sand filtration for many years. In general there are two types of filters which are known as slow sand filters and rapid sand filters. Slow sand filters consist of a layer of sand bed of 0.6-0.9 m depth (0.15 to 1 mm diameter) supported on the bed of gravel 0.3-0.45m thick, (through which water is filtered at low flow rates (Graham, 1988; Sastry *et al*., 1996). Filtration rates are as much as fifty times slower than those of rapid sand filters; consequently slow sand filters require significantly more surface area in order to filter comparable volumes of water (Clark, 1997). Rapid sand filters consist of a layer of coarse sand 0.6 to 0.75 m thick (0.5 to 2 mm diameter) laid on the top, with a layer of graded gravel of 0.45 m thick below (Graham, 1988; Sastry *et al*., 1996).

Slow Sand Filtration (SSF) is commonly used as an appropriate water treatment process and more suitable for developing countries. This method could significantly improve the physical and bacteriological qualities of water without the use of any chemicals. However, the filters are frequently blocked due to the accumulation of suspended solids and had caused unacceptable short filter runs. For SSF, pretreatment of the raw water is almost a necessity if the raw water has a turbidity of more than 50 NTU for period longer than a few weeks. Roughing filters are often used for pretreatment because of their effectiveness in removing suspended solids (Burch and Thomas, 1998).

Other types of filters have been used to meet raw water qualities at a pretreatment stage. Intake and dynamic filters are often applied as pretreatment before slow sand filters. These filters are usually cleaned hydraulically by fast filter drainage. Sequences of different prefiltration stages are frequently the most cost-effective option by applying the multi-barrier concept and, hence, providing an efficient way of improving the microbiological water quality (Wegelin, 1996).

2.2 Background on Roughing Filtration

Filtration is a process for separating suspended impurities from water by passing through porous media. Particle removal is one of the main objectives of filtration (Sastry *et al.*, 1996; Clasen, 1998). Water supply treatment plants generally use sand filters to produce clear water. Most sand filters have maintenance and operation problems due to lack of pre-treatment system for the reduction of turbidity and suspended solids. Gravel filtration has been used in water treatment since the early 1800s, when it was first used in Scotland to pre-treat water prior to sand filtration. Gravel filtration soon disappeared due to the advent of chemical and mechanical water treatment. However, gravel filtration reemerged in the 1970's and 1980's mainly in developing countries, because those roughing filters do not require sophisticated mechanical equipment or the use of chemicals (Cleary, 2005). Roughing filters are the most common type of pre-treatment system, which are used before slow sand filters in order to reduce the raw water turbidity and suspended solids (Wegelin, 1986; Jayalath and Padmasiri, 1996; Ali, 1998; Ingallinella *et al.*, 1998).

Therefore, roughing filtration technology is used as pretreatment to polish the raw water quality for the improvement of performance of slow sand filtration. But it may be used without slow sand filtration if raw water originates from well protected catchment area and having minor bacteriological contamination (Wegelin, 1996). Therefore in rural water supply systems roughing filtration becomes an appropriate technology. Besides that roughing filter can be maintained easily, does not need any chemicals, has long operational time and can be operated and maintained by trained local caretakers (Wegelin, 1986; Reed and Kapranis, 1998).

Wastewater also needs to be treated because it contains bacteria and viruses, some of which can cause diseases to human. Besides, it also contains BOD sources that can deplete oxygen in receiving water resulting in aquatic organisms becoming stressed, suffocate and die (Spellman and Drinan, 2000). Moreover, it contains high levels of nutrients that are toxic to fish and invertebrates and creates nuisance conditions in the receiving environment. To protect the environment, such kinds of materials have to be removed prior to the water being discharged back to the environment (Wikipedia, 2005).

Roughing filters can improve the quality of wastewater after treatment. Roughing filters are intended to treat particularly strong or variable organic load. The design of the roughing filter allows high hydraulic loading and high flow rate. The resultant effluent is usually within the normal range for conventional treatment processes (Wikipedia, 2005)

2.3 Classification of Filter

The two criteria for filter classification are size of filter media and rate of filtration. Rapid sand filter and slow sand filter are different from intake filter and roughing filter according to their filter media size. The coarse filter media and the low flow rates applied to roughing filtration. Table 2.1 elucidates the differences of filter material sizes and flow rates of each filter.

Table 2.1 Classification of Filters (Source: Graham, 1988)

Characteristics	intake filtration	roughing filtration	rapid sand filtration	Slow sand filtration
filter material size (mm)	6 - 40	4 - 25	0.5 - 2	0.15 - 1
filtration rate (m/h)	2 - 5	0.3 - 1.5	5 - 15	0.1 - 0.2

2.4 Types of Roughing Filters

There are various types of roughing filters such as downflow roughing filters (DRF), horizontal flow roughing filters (HRF) and upflow roughing filters (URF). The layouts of different roughing filters are shown in Figure 2.2. The selection criteria for types of roughing filtration are based upon raw water quality such as turbidity, suspended solids, color, iron and fecal coliform levels (Wegelin, 1996; Wolter and Mwiinga, 1997).

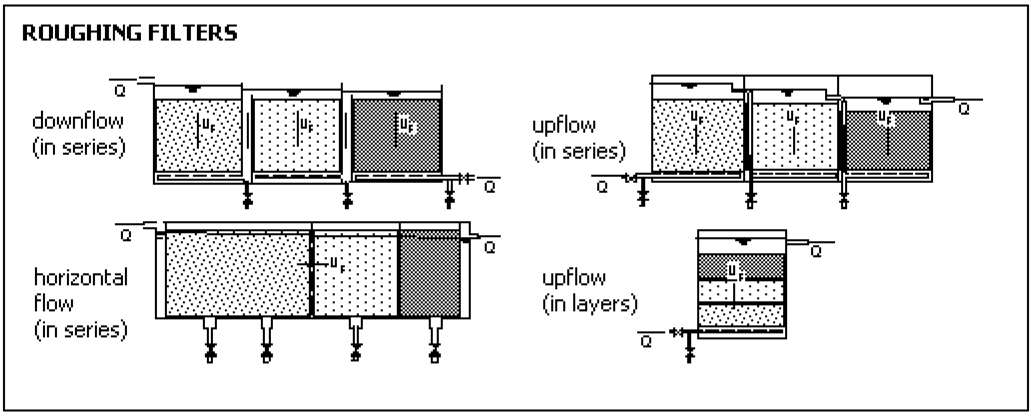

Figure 2.2: Types of Roughing Filters (Source: Wegelin, 1996)

Downflow roughing filter consists of 3 or 4 individual filter boxes, each box is filled with filter media, with the coarsest media in the first compartment and the finest media in the last compartment. Water flows downward through each media compartment.

Horizontal flow roughing filtration consists of coarse gravel filter media arranged in series from coarse to fine sizes in the direction of flow. It allows the treatment of water with considerable contamination higher than the levels of slow sand filter. For this reason roughing filters are often used before slow sand filters. Roughing filters have turbidity removals ranging from 60 to 90%. Additionally it could achieve similar reductions of coliform organisms without using any chemicals (Wegelin, 1986; WHO, 2004). The advantage of horizontal flow roughing filter is its extended bed lengths and solid storage capacity, resulting less cleaning frequency. The disadvantage includes large space requirement.

Upflow roughing filter can generally be divided into two types, upflow roughing filter in series and upflow roughing filter in layers. An upflow roughing filter in series is similar to the downflow roughing filter. The difference is that water will flow upward through each media compartment. Although upflow and downflow roughing filters perform similarly, upflow roughing filters are recommended for ease of cleaning (Wegelin, 1996).

Upflow roughing filter in layer consist of one filter box, with multiple layers of filter media, ranging from coarse media at the bottom to fine at the top and water flows in upward direction. The advantage of this filter is that it has much lower space and cost requirement than other types of roughing filters.

In general, optimal treatment in roughing filters can be achieved by using more individual compartments. That means, a 3 stage roughing filter is expected to perform better than a 2 stage roughing filter. Upflow roughing filters are more efficient in solid removal than other types of roughing filters (Cleary, 2005). However, since vertical flow (upflow or downflow) roughing filters have a smaller filter depth compared to horizontal flow roughing filters, it is recommended that vertical flow filters should be limited to treating raw water with turbidities less than 150 NTU (Wegelin,1996).

2.5 Filter Materials

Graham (1988) described that filter material originally used in the roughing filter was gravel, later it was replaced by any inert, clean, insoluble and mechanically resistant material. Wegelin (1996) described that the filter material should have a large specific surface to enhance the sedimentation process in the roughing filter, and high porosity to allow the accumulation of the separated solids. According to Wegelin (1996), neither the roughness nor the shape or structure of the filter material have a great influence on the filter efficiency. Graham (1988) suggested that on the practical side, economic considerations besides availability of appropriate material are important factors in the selection of the filter media.

As filter media, gravel from a river bed or from the ground, broken stones or rocks from a quarry, broken burnt clay bricks, plastic material either as chips or modules, burnt charcoal and coconut fibre were used (Wegelin, 1996). In horizontal flow roughing filtration project implemented in Java, Indonesia, the coarse gravel fraction has been replaced by “injuk”, a local palm fibre. Apparently, this fibre does not release taste or odour to the water. This interesting fibre might be a potential filter material due to its large specific surface area and high porosity (90-92%) which considerably increase retention time of the water in the filter and enhance filter efficiency (Graham, 1988).

2.6 Cleaning of Roughing Filter

Roughing filters need to be cleaned for the purpose of removing accumulated particulate matter and replenishing the solid storage capacity of the filter. Cleaning can recover initial head loss (Cleary, 2005). Pacini *et al.* (2005) found that the cleaning of roughing filter with a final headloss of 22 cm could be recovered to 15 cm. The frequency of cleaning is dependent on the loading of particulate matters and biological activity in the filter (Wegelin, 1996).

2.7 Roughing Filter for Wastewater Reuse

The wastewater produced from Mexico City was transported to the valley of Mezquital, where it was used, to irrigate approximately 90,000 ha of agricultural lands. Even though the reuse of wastewater had increased the productivity of maize, oaths, alfalfa, sorghum and wheat between 71% and 150%, on the other side a corresponding increased in gastro-intestinal illness by helminthes infection, had been reported. Children from 0-4 years of age had been shown to suffer up to 16 times the normal rate of such infection. Therefore, to protect the health of agricultural workers, and their families the WHO has adopted the regulation that all types of agricultural irrigation water should contain less than 1000 fecal coliforms (MPN)/100ml (Jimenez *et al*., 2000). To meet that requirement, Mexican National Water Commission opted to use primary treatment by filtration. In their research, the model of roughing filter was used. According to results presented, the roughing filtration system was able to consistently produce effluents with fecal coliform less than 1000 (MPN)/100ml with 68% removal (Jimenez *et al*., 2000).

Application of treated wastewater for irrigation has become a common practice worldwide and a centre of attention to scientists and technologists in developing countries (Hamoda *et al*., 2004; Lubello *et al.,* 2004). One of the treatment techniques which have been intensely scrutinized is the wastewater stabilization pond systems. However that technique has been found costly to construct and expensive to operate and maintain. Roughing filtration was the option for low cost and appropriate technology to treat wastewater. Combination of roughing filter and constructed wetland could remove total suspended solid of 89.35%, BOD_5 of 84.47% and fecal coliform of 99.99 % (Kimwaga *et al*., 2004).

2.8 Roughing Filter Theory

Roughing filtration is more of an art than a science. Numerous researchers have tried to describe the filtration mechanisms in mathematical models applying either the phenomenological or the trajectory approach. In the first approach important variables, such as filtration rate, filter size, depth and porosity are used to describe filter efficiency. In the second approach it focuses more on transport mechanism of the particles (Wegelin, 1996).

While the contaminated water passes through the filter, microbes and other particles are removed. Although the removal mechanisms are not well understood, they are believed to be a combination of biological, physical and chemical mechanisms. Specific mechanisms may include biological action, attachment of microbes to filter media by electrochemical force and physical straining (WHO, 2004).

2.8.1 Flow Rate and Head Loss Control

Flow rate is an important factor affecting removal in roughing filter. In particular, sedimentation and biological mechanisms depend on the filtration rates (Cleary, 2005). Lower filtration rates allow less turbulent conditions in the filter media interstices and facilitate gravitational sedimentation, reduces fluid shear on the deposited particles, and increase the hydraulic retention time in biologically active regions of the filter.

The main objective of roughing filter is to reduce the amount of solid matter from the raw water. Filters are usually operated at the filtration rate of up to 1.5 $m^3/m^2/h$ and size of filter material ranged between 4 mm and 20 mm. Head loss in a roughing filter is usually small. Head loss can be recorded as water level difference between the inlet and outlet water level (Wegelin, 1996). The head loss in a filter can be calculated as;

$$h = 1.07L\frac{C_D V^2}{\psi g d f^4} \tag{2.1}$$

Where h = head loss (m)

L = filter depth (m)

C_D = (24/Re) + (3/√Re) + 0.34 (the drag coefficient)

Re = Vd/μ (dimensionless Reynolds Number)

μ = kinematics viscosity of fluid (m^2/s)

d = particle diameter (m)

Ψ = dimensionless shape or sphericity factor (<1)

g = gravitational constant (m^2/s)

V = flow rate ($m^3/m^2/h$)

f = porosity the ratio of (volume voids)/(total bed volume)

The head loss is important in determining the filter efficiency. The filters should be cleaned when the filter units reach an unacceptably high head loss (Gray and Osborne, 1995). Although conventionally slow sand filters need to be frequently cleaned by complicated mechanical equipments, a well designed roughing filter will work for several months between two subsequent cleanings (Wegelin, 1986). The development of head loss in the filter is small during the initial period of operation, it later increases with most of the head loss occurring on the top dirty surface of the filter media, known as ripening (Farooq and Al-Yousef, 1993).

2.8.2 Removal Mechanisms of Roughing Filter

Water entering roughing filter may include small suspended materials such as leaves, small stones and even debris of wastes. Screening process could remove suspended particles which are larger than the pore size of filter media. Figure 2.3 illustrates the screening mechanisms in roughing filter. The smallest pore size is roughly taken as one sixth of gravel size. Thus, it is feasible that a 2 mm diameter media could strain out particles larger than 330 µm in size. Since most suspended particles travelling in water are not larger than pore size of the media, it could not be removed by screening mechanisms. However, the pore sizes of the media progressively decrease due to particle deposition and biofilm growth. Thus the enhanced screening has been attributed to previously removed particles in roughing filters. Therefore, screening becomes more effective as the pore size of medium decreases and thus more effective in capturing particles that are even smaller in size than the initial pore size (Weber-Shirk and Dick, 1994; Wegelin, 1996).

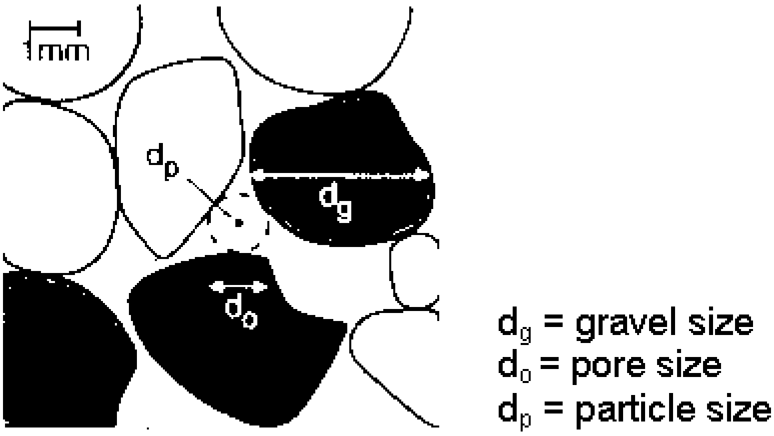

Figure 2.3: Screening of Particle on Filter Media (Source: Wegelin, 1996)

Sedimentation is the main solid separation process in roughing filters. Sedimentation occurs when the mass density of particle is greater than that of water and its settling velocity causes the particle to deviate from the flow path and settle onto the media surface. Thus, sedimentation is probably more important for suspended particulates removal. Figure 2.4 illustrates the principles of sedimentations on the filter media. To achieve adequate solid removal efficiencies, roughing filters need to be operated under laminar flow conditions (Wegelin, 1996).

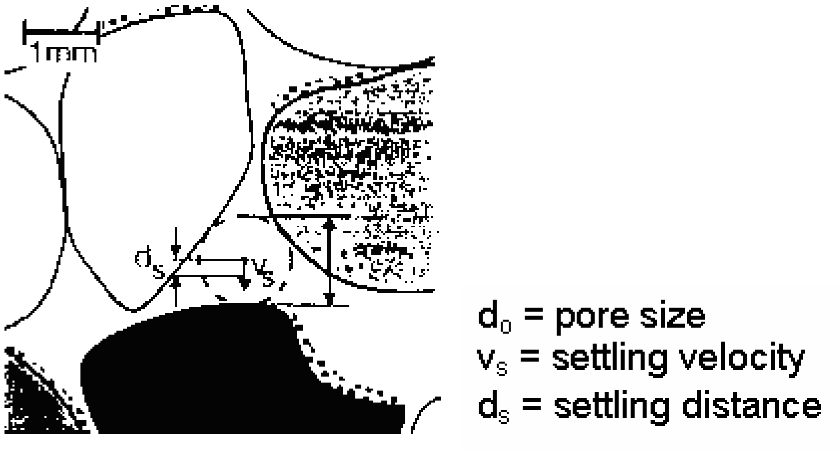

Figure 2.4: Sedimentations on Filter Media (Source: Wegelin, 1996)

The roughing filter can be considered as a sedimentation basin, where the filter media provides a large surface area and short settling distances for particle settling (Wegelin, 1996). In conventional sedimentation basins, particles have to reach a settling distance of 1 to 3 meters, whereas in roughing filters, the settling distance to the gravel surface is only a few millimeters. Therefore, solid particles flowing through the filter touch and deposit on media surface within a few millimeters. Therefore roughing filtration is more effective process for particle removal than plain sedimentation. Particles deposit onto media grains in dome-like formations (Wegelin, 1986). The most particle accumulation occurs in the bottom of the filter (Cleary, 2005).

Sedimentation of particles in the voids of filter media is part of the treatment processes for the removal of suspended particles in roughing filter. The process is known as settling or clarification. The efficiency of this process is measured by turbidity removal. It depends on size of particle and settling rate. Sedimentation is a treatment process in which the velocity of the water is lowered below the suspension velocity and the suspended particles settle out of the water due to gravity. The settling velocity is influenced by mass density, size and shape of particle, as well as by viscosity and hydraulic conditions of water. There is basic formula to calculate settlement velocity for a spherical particle by using Stoke's law and it is given as:

$$v = \frac{gd^2(p_p - p_w)}{18\mu} \tag{2.2}$$

Where:

v = settling velocity in (cm/s)

g = acceleration due to gravity in (cm/s^2)

d = diameter of particle in (cm)

ρ_p = particle density in (g/cm^3)

ρ_w = fluid density in (g/cm^3) and

μ = fluid viscosity in (g/cm/s)

Stoke's Law gives the relationship between the settling rate, particle size and density. From the equation, for all other parameters being constant, dense particles settle faster, larger particles settle faster, and more viscous water causes particles to settle slower.

Interception is the process which enhances particle removal in the filter. Interception occurs when deposited particles accumulate on the filter media that gradually reduce the pore size. Figure 2.5 elucidates the principle of accumulation of particles due to interception effects. Suspended particles travelling in roughing filter are obstructed to continue forward due to reduction of pore size. Therefore particles will collide with each others and are packed like sardines and lose energy to go forward. Finally they will deposit on filter medium. Thus, removal efficiency becomes higher (Wegelin, 1996).

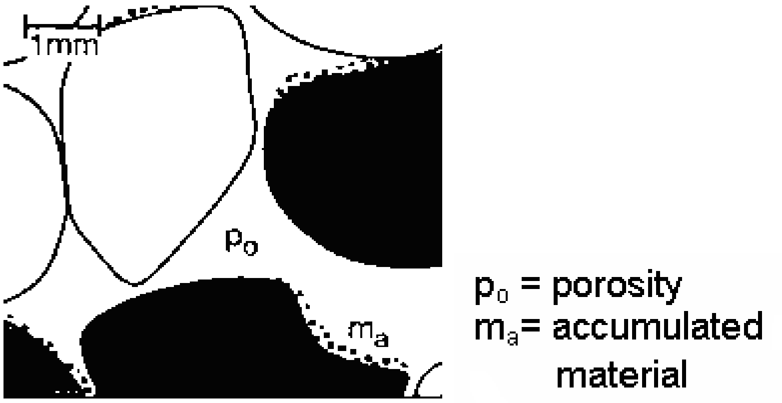

Figure 2.5: Interception on Filter Media (Source: Wegelin, 1996)

The combination of mass attraction and electrostatic forces generally enable the particles to keep in contact with other solids particles and the filter materials. These two forces could settle particles in a short distance on the grain surface. For these reasons these two forces are important in roughing filters (Wegelin, 1996).

Biological activity also develops in the filter when particles of organic origins are deposited on the filter material. Bacteria and other microorganisms will form a sticky layer around the gravel. Particles travelling in water readily adhere to this organic material and are finally retained in the filter (Wegelin, 1996). The bacteria and microorganisms covered on the filter media use the pollutions in the waste water as their food source and convert it to carbon dioxide (Moye, 2004). The development of a bacterial biofilm on the filter media improves the removal ability of the filter. This increased removal efficiency occurs for all particle sizes initially, but eventually only continues for small sizes and possibly becoming negative for larger particles. Captured particles assist in the collection of subsequent particles by partially blocking and restricting passage through the pores. When more time elapses between collisions of particles on the media surface and those in solution, the first collected particle may migrate to the bottom of the grain and greatly reduce the opportunity for interaction with the next incoming particle. Thus, the removal efficiency is greater and ripening is quicker when the influent concentration is greater (Clark *et al*., 1992; Cole, 1998; Mwiinga *et al*., 2004b).

2.8.3 Transformation Mechanisms in Roughing Filter

With the passage of time, the new particles settle on the top of previously settled particles and turn it into a firm structure of accumulated material. Therefore it is no longer exposed with fresh water. Then biochemical oxidation starts to convert organic matter into small aggregates, carbon dioxide and inorganic salts. Turbidity and color also undergo changes, while iron and manganese traces are removed (Wegelin, 1996).

Microbiological activity also plays an important role in roughing filters. Microorganisms such as fecal coliforms travel together with suspended particles before entering a roughing filter. When they entered the roughing filter they also remained together as particles settled on the filter material. As the time passes by, fecal coliforms start to starve, are attacked by other microorganisms and finally die (Wegelin, 1996; Sastry *et al*., 1996; Pacini, 2003).

2.9 Factors Affecting Removal in Roughing Filters

The major parameters that affected suspended solids removal by roughing filters were filter media size, filtration rate and bed depth. Generally, removal efficiency increases with decreasing filter media size, decreasing filtration rate and increasing filter bed depth (Cleary, 2005).

The filter media size is an important variable. An increased efficiency in the treatment has been observed with decreasing filter media size, which indicates the importance of straining (Wegelin, 1996). Higher removals can be obtained due to smaller interstices between smaller media, as well as the larger surface area available, which allow more adsorption. A smaller size of filter media will have a larger total surface area available for biofilms to grow on, and therefore more biofilm can be exposed to raw water. Therefore, removal efficiency increases.

The empty space or pore size within a filter medium is important for determining the right filter size and efficiency. Pore size is a measure of how much of the medium consists of empty space. The filter efficiency depends on the ratio of filter media surface area to its volume, which means total specific surface area (SSA) per cubic metre. Despite this enormous SSA, sand would make a poor filter medium because the small particle size would soon lead to blockages. Because of the dense packing, any flow through the sand would be very slow. Therefore despite its massive surface area, the volume of water that could be treated per hour would actually be quite small (FishDoc, 2004). For a medium such as gravel, it is larger in size and less in SSA that would make it less prone to blocking. Special media such as filter matting, plastic or sintered glass, have both a large SSA and a generous void space. In fact, many of them are more than 90% void or empty space. This makes blockage almost impossible (FishDoc, 2004).

Filtration rate also has a significant influence on the particle removal. Many reports described that good removals in the roughing filters were achieved at low filtration rates. It is attributable that low filtration rates give support to retain particles that are gravitationally deposited to the upper side of filter media. It is important to have laminar flow conditions. In Figure 2.6, Wegelin (1996) revealed that filtration rate greatly influence the filter efficiency. Flow conditions are described by Reynolds number. At Reynolds number less than 10, laminar flow can be expected. Removal efficiency increases with decreasing Reynolds Number (Re). According to Figure 2.6, turbidity removal was 40% at a Re of 8, whereas removal was greater than 80% at Re of less than 3. Wegelin (1986) described that at increased filtration rates, coarse particles penetrated deeper into the bed, clogged the finer gravel media, and re-suspended pre-deposited particles resulting in decrease in filter efficiency.

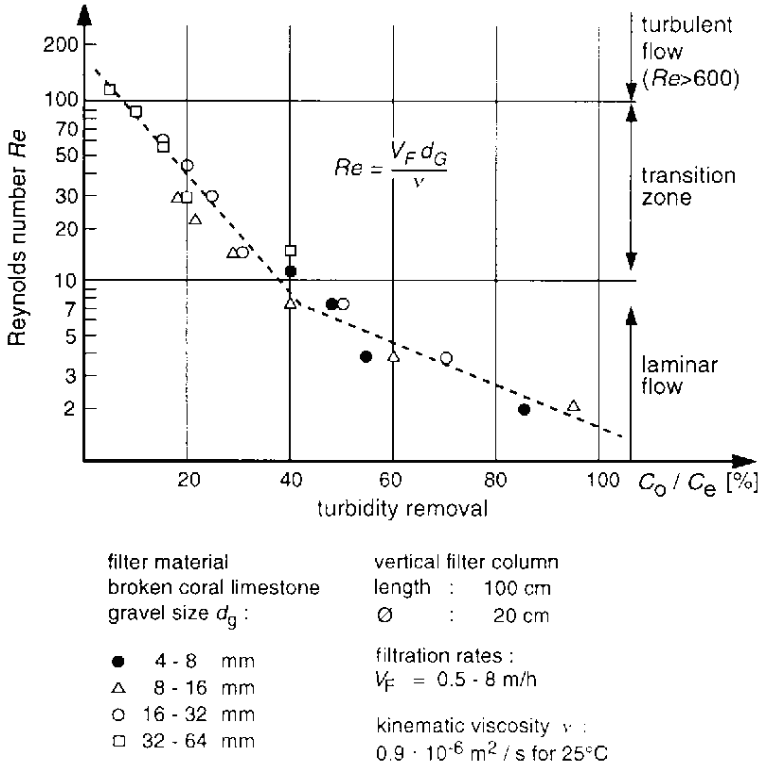

Figure. 2.6: Roughing Filter Efficiency in Correlation to flow conditions (Source: Wegelin, 1996)

Filter bed depth also affects efficiency of roughing filters. While particles deposits on the filter bed, pore spaces becomes smaller. As suspended particles, accumulate on a filter bed, the pressure drop through the filter will be increased (Culligan, 2005). Operating with high-pressure drop may increase the chance of detachment and penetration of detached solids will move deeper into the filter bed. Therefore, increasing filter bed's depth will improve overall performance and coliform removal. On the contrary, Reed and Kapranis (1998) described that there was no significant difference between two bed depths of 0.75 and 1.0 m. Although they did not discuss in detail, the reason might be that they used large size filter media in the experiment.

Lin *et al*., (2006) indicated that improved cumulative removal efficiencies are typically correlated to longer filter lengths at the expense of pressure drop. Without affecting the removal efficiency, the filter length and thus the pressure drop can be reduced with the use of multiple media sizes, as illustrated in Figure 2.7. The larger solids particles are removed by coarse media, medium size filter media can polish and the finest media could remove the remaining traces of solid matters (Wegelin, 1996).

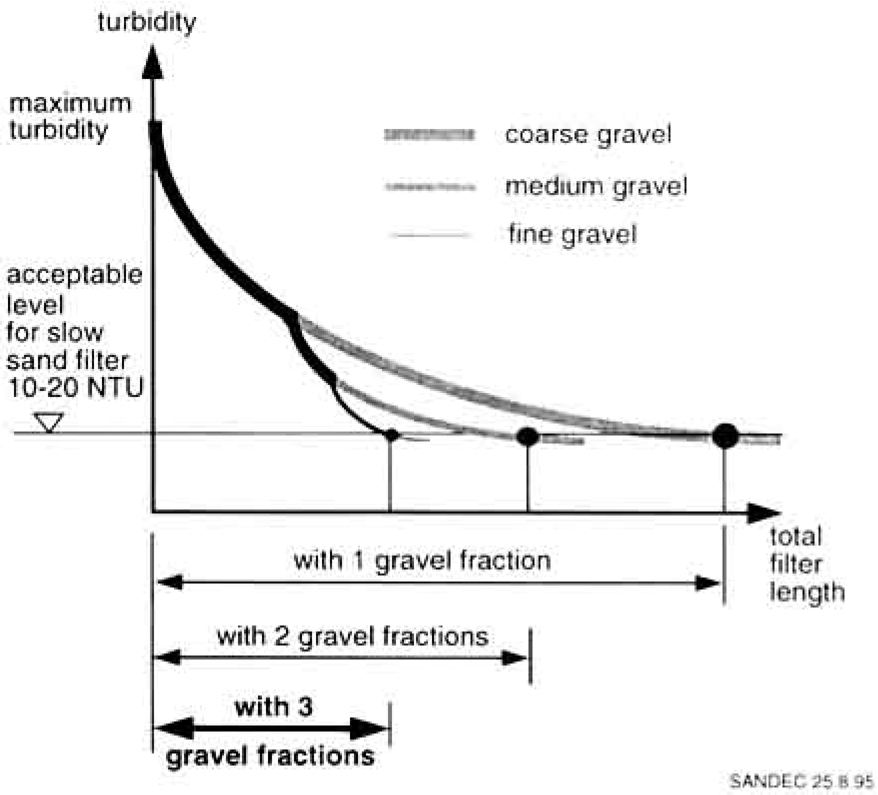

Figure 2. 7 : Significance of Turbidity Reduction along Roughing Filter Length (Source : Wegelin, 1996)

Removal of particulate matters in roughing filter is also dependent on raw water characteristics. Thus, it is important to study the characteristics of the given source of water in designing a roughing filter. Wegelin (1996) revealed that roughing filters were good for removal of major solid particles and for highly turbid waters. Clark (1997) described filtration performance depends on the source of water quality (types and concentration of natural organic matter and suspended particles) and viscosity changes in raw water would affect filter's performance.

Beside, the particle sizes and nature (organic and inorganic) also have a significant influence on its removal in roughing filter (Wegelin, 1996). Figure 2.8 (Wegener, 2003) strongly supported that suspended solid removal was less than 50% at the particle size of 5-10 μm and almost 100 % at particle size of 50-100 μm in the trickling filter using low density plastic filter media.

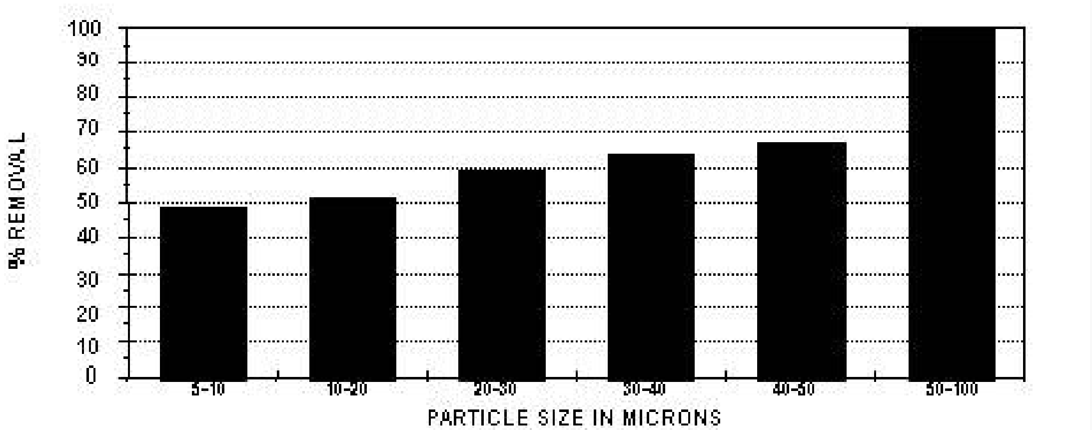

Figure 2.8: Percentage Removal Versus Particle Size (Source : Wegener, 2003)

In summary, performance of roughing filter depends on influent solids concentration, particle size, filter media size, bed depth and filtration rate. Roughing filter design becomes more of an art than science when attempting to determine the optimal combination of media size and bed depth for particular source of water (Clark *et al*., 1997; Wegelin, 1996).

2.10 Removal Capabilities of Roughing Filter

In the following section, removal capabilities of roughing filtration studies are presented. The major parameters discussed in this section are removal of turbidity, suspended solids, total coliform and biochemical oxygen demand. The following section is a performance comparison of previous researches.

2.10.1 Turbidity Removal in Roughing Filter

Roughing filters could achieve peak turbidity removal ranging from 60% to 90%. Generally, the more turbid the water, the greater in reduction could be achieved (WHO, 2004). Roughing filters could remove clay particles more effectively when the filter was ripen with algae cells (WHO, 2004). Rooklidge *et al*. (2004) found that turbidity removal using limestone filter media with average porosity of 0.46 was 79%.

Mahvi *et al.* (2004) revealed that the performance of horizontal flow roughing filter could improve by applying coagulant prior to filtration. They have shown that a horizontal flow roughing filter using three different size of 12-18 mm, 8-12 mm and 4-8 mm filter media with flow rate of 2 m/h, has produced good effluent quality, less than 2 NTU from raw water quality of 200-400 NTU. Culligan (2005) described that chemical pretreatment could increase filtered water clarity, measured in NTU in the range of 93%-95% removal. WHO (2004) also supported that addition of alum before treatment with a horizontal roughing filter could improve the filter's performance for turbidity, color, organic carbon, head loss and filter run time. Mwiinga *et al*. (2004a) also supported that adding lower coagulation dose by gravity could treat higher turbidity raw water and enhanced turbidity removal in upflow gravel roughing filters. However, none of them describes the effect of the variation in dosage amount of coagulant on the filter performance.